The NuMI Neutrino Beam and Potential for an Off-Axis Experiment

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Abstract. The Neutrinos at the Main Injector (NuMI) facility at Fermilab is under construction and due to begin operations in late 2004. NuMI will deliver an intense ν_μ beam of variable energy 2-20 GeV directed into the Earth at 58 mrad. Several aspects of the design are reviewed, and potential limitations to the ultimate neutrino flux are described. In addition, potential measurements of neutrino mixing properties are described.

1. Introduction

Within the context of 3-flavor neutrino flavor mixing [1], the atmospheric neutrino experiments [2] have observed $\nu_\mu \to \nu_\tau$ oscillations with $|\Delta m^2_{23}| = (2-4) \times 10^{-3}$ eV^2 and $\theta_{23} \approx \pi/4$, while solar neutrino experiments[3] indicate $\Delta m^2_{21} = (2{-}10)\times 10^{-5}$ eV^2 and $\theta_{12} \approx \pi/6$. Unlike the quark mixing matrix, neutrino mixing appears near-maximal. Only upper bounds [4] exist on the process $\nu_\mu \leftrightarrow \nu_e$ at the atmospheric Δm^2. † If the angle θ_{13} is not zero, and in fact is reasonably large, then the potential exists at conventional long-baseline neutrino beams to measure this rare process and to use it to observe CP violation in the lepton sector and determine the mass hierarchy of neutrinos [6].

To first order the appearance of ν_e in a pure ν_μ beam in vacuum is given by $P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27L\Delta m^2_{23}/E_\nu)$, which is approximately $\frac{1}{2}\sin^2 2\theta_{13}$ at the atmospheric L/E_ν. Given the Chooz bounds [4] an experiment to observe this transition must be sensitive at the 1% level. This transition is modified in matter by a factor $(1 \pm 2E_\nu/E_R)$, where $E_R \sim 13$ GeV is the resonance energy in the earth's crust at the atmospheric Δm^2. Neutrino (antineutrino) transitions are enhanced (depreciated) by this factor under the normal mass hierarchy, while the opposite occurs for an inverted mass hierarchy. This transition is also modified by a factor which depends on the phase δ of the neutrino mixing matrix, potentially yielding the opportunity to observe a CP-violating difference between $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ transitions. Figure 1 shows the probabilities for these transitions at an L/E_ν accessible with the NuMI beam.

Figure 2 shows the neutrino spectra possible in NuMI[7], both for the initial MINOS experiment[8] on-axis, and at three possible off-axis angles, where the resulting neutrino energy from off-axis pion decays becomes rather narrowly peaked and near-independent of pion energy due to two-body decay kinematics[9]. At 14 mrad, the

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† The LSND experiment has published evidence[5] for $\overline{\nu}_\mu \to \overline{\nu}_e$ at $\Delta m^2 \sim 0.1$ eV^2 which, if confirmed, signficantly modifies the 3-flavor mixing scheme above.

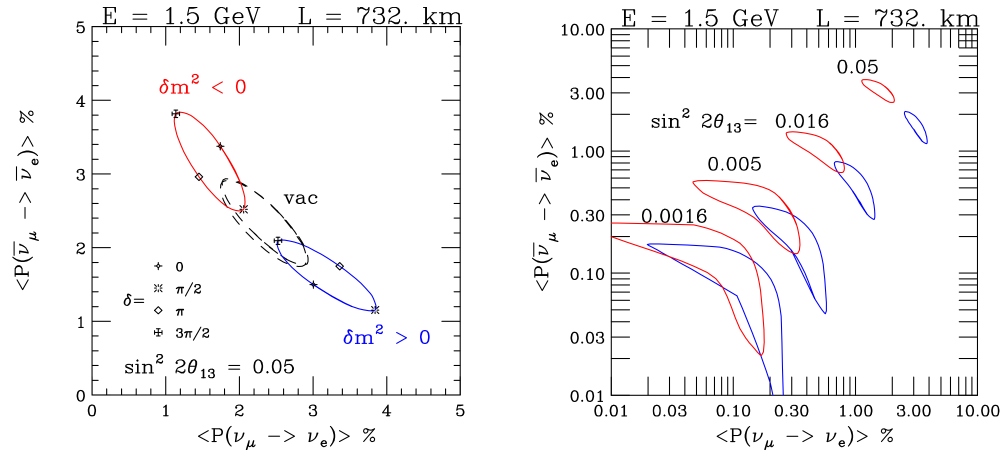

Figure 1. The expected oscillation probability for $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ evaluated at L/E=500 km/GeV and $|\Delta m^2_{31}| = 3 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0$, $\Delta m^2_{21} = +5 \times 10^{-5}$ eV^2, $\sin^2 2\theta_{12} = 0.8$, and a constant matter density $\rho = 3.0$ g/cm^{-3}. (Left) evalated ignoring matter effects (black ellipse) and including matter effects for positive (blue) and negative (red) Δm^2_{31}. The values of $\sin^2 2\theta_{13}$ and δ are indicated. (Right) The same bi-probability plots for several possible values of $\sin^2 2\theta_{13}$.

peak is near oscillation maximum, and the intrinsic ν_e from the beam is of order 0.4% under the peak (see Figure 3), coming primarily from muon decays. Of greater magnitude is the potential background to a ν_e appearance search from neutral current ν_μ interactions, which leave a small hadronic visible energy in the detector (see Figure 3). A study of detector designs for an off-axis experiment will be required to assess how frequently these are misidentified as charged current ν_e interactions.

The event rate spectra in Figures 2 and 3 are possible with the baseline NuMI beam design, so that if $\sin^2 2\theta_{13} = 0.1$ (at the Chooz limit), a 20 kt NuMI experiment at 712 km with similar ν_e efficiency and NC rejection as SuperK might observe 86 oscillated ν_e's in 5 years, with a background of 10 NC's and 10 intrinsic beam ν_e. For JHF [10], the similar numbers are 123 signal, 11 beam ν_e, and 11 NC's in their Phase I. Note that the lower proton beam power at NuMI is mitigated by the higher cross sections for 1.8 GeV neutrinos. To measure matter effects (hence the sign of Δm^2_{13}) or the phase δ will require running in $\overline{\nu}_\mu$ mode and additional upgrades to the proton beam intensity from the Main Injector [11] because of the lower antineutrino event rates. Both these measurements benefit from longer baseline distances, again motivating the need for proton intensity upgrades and furthermore larger detectors.

2. The NuMI Beamline

NuMI is a tertiary beam resulting from the decays of pion and kaon secondaries produced in the NuMI target. Protons of 120 GeV are fast-extracted (spill duration 8.6 μsec) from the Main Injector (MI) accelerator and bent downward by 58 mrad toward Soudan, MN. The beamline is designed to accept 3.8×10^{13} protons per pulse (ppp). The spill repetition rate is 0.45 Hz, giving 4×10^{20} protons on target per year.

The Main Injector is fed up to 6 batches from the Booster accelerator, of which 5 batches are extracted to NuMI. It is likely that when Main Injector operates at

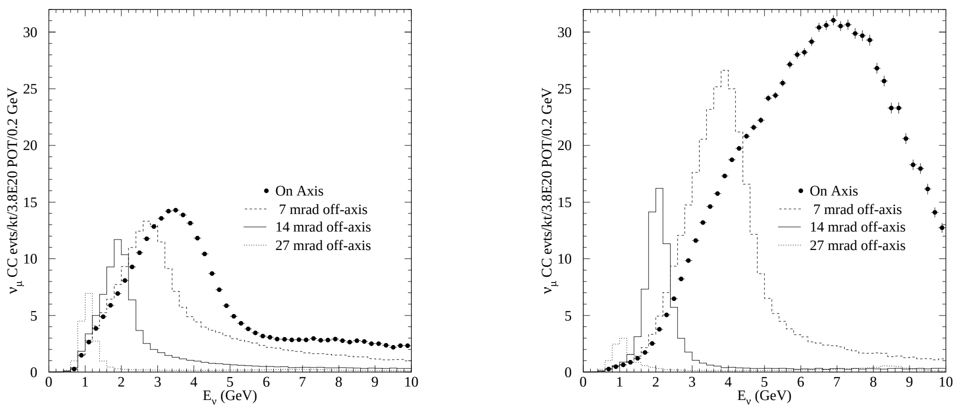

Figure 2. Energy spectra of charged current events expected at a far detector location 735 km from Fermilab at various off-axis angles for the NuMI low-energy beam setting (left) and the medium-energy setting (right).

full intensity in multi-batch mode it will have $\Delta p/p = 0.003$, and emittances up to 40π mm-mrad. Initiatives to produce higher intensity beam from the Main Injector without constructing a proton driver upgrade, including barrier RF stacking of more than 6 Booster batches, could increase the beam intensity by a factor of 1.5 at the expense of some emittance growth.

The NuMI optics will maintain losses below 10^{-5}. A recent redesign of the primary beamline replaced a long free drift region with a FODO lattice, increasing the

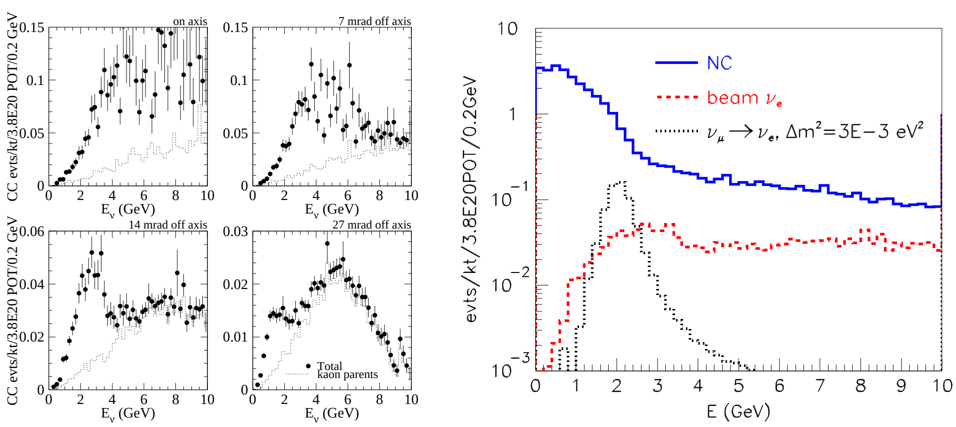

Figure 3. (Left) Spectrum of ν_e events expected at a far detector 735 km from Fermilab for several off-axis angles. The ν_e rates are plotted in total (points) and the component from $K \rightarrow \pi e \nu_e$ decays. (Right) Spectrum of potential $\nu_\mu \rightarrow \nu_e$ oscillation signal with $|U_{e3}|^2 = 0.01$ (black histogram) and for two potential ν_e backgrounds: real ν_e from muon and K_{e3} decays (red histogram) and the total visible (hadronic) energy from ν_μ neutral current events before any rejection criteria are applied (blue histogram).

momentum acceptance to $\Delta p/p = 0.0038$ at 40π mm-mr. Injection errors of $\sim$1 mm lead to targeting errors of $\sim$0.5 mm. The beamline has 21 BPM's of 50 μm accuracy, 19 dipole correctors, and 10 retractable secondary emission foil profile+halo monitors.

The primary beam is focused onto a graphite production target [12] of $6.4\times 20\times 940$ mm^3 segmented longitudinally into 47 fins. The target is water cooled via stainless steel lines at the top and bottom of each fin and is contained in an aluminum vacuum can with beryllium windows. It is electrically isolated so it can be read out as a Budal monitor [13]. The target has a safety factor of about 1.6 for the fatigue lifetime of 10^7 pulses (1 NuMI year) given the calculated dynamic stress of 4×10^{13} protons/pulse and 1 mm spot size. A prototype target was tested in the Main Injector at peak energy densities exceeding that expected in NuMI. Studies indicate that the existing NuMI target could withstand up to a 1 MW proton beam if the beam spot size is increased from 1 mm to 3 mm [14].

The particles produced in the target are focused by two magnetic 'horns' [15]. The 200 kA peak current produces a toroidal field which sign- and momentum-selects the particles from the target. The relative placement of the two horns and the target optimizes the momentum focus for pions to a particular momentum, hence the peak neutrino beam energy. The neutrino spectra from two energy settings, called the 'low energy' (LE) and 'medium energy' (ME) beams, are shown in Figure 2. To fine-tune the beam energy, the target is mounted on a rail-drive system with 2.5 m of travel along the beam direction, permitting remote change of the beam energy without accessing the horns and target [16]. Measurements on a horn prototype show the expected $1/r$ fall-off of the field to within a percent. The horns are designed to withstand 10^7 pulses (1 NuMI year), and tests of the prototype horn have so far achieved this.

The particles are focused forward by the horns into a 675 m long, 2 m diameter steel pipe evacuated to $\sim$ 0.1 Torr. This length is approximately the decay length of a 10 GeV pion. The entrance window to the decay volume is a spherical bell-shaped steel window 1.8 cm in thickness, with a 1.5 mm thick aluminum window 1 m in diameter at its center where 95% of the entering pions traverse. The decay volume is surrounded by 2.5-3.5 m of concrete shielding. Twelve water cooling lines around the exterior of the decay pipe remove the 150 kW of beam heating. Earlier plans to instrument the decay volume with a current-carrying wire (called the 'Hadron Hose' [17]) which would provide a toroidal field that continuously focuses pions along the decay pipe length, have been abandoned due to budget constraints.

At the end of the decay volume is a beam absorber consisting of a $1.2\times1.2\times2.4$ m^3 water-cooled aluminum core, a 1 m thick layer of steel blocks surrounding the core, followed by a 1.5 m thick layer of concrete blocks. The core absorbs 65 kW of beam power, but is capable of taking the full proton beam power of 400 kW for up to an hour in the event of a mistargeting. In the event of a proton intensity upgrade the core would require no modification, but the steel blocks might require cooling.

Ionization chambers are used to monitor the secondary beam. An array is located immediately upstream of the absorber, as well as at three muon 'pits', one downstream of the absorber, one after 8 m of rock, and a third after an additional 12 m of rock. These chambers monitor the remnant hadrons at the end of the decay pipe, as well as the tertiary muons from π and K decays. When the beam is tuned to the medium energy configuration, the pointing accuracy of the muon stations can align the neutrino beam direction to approximately 50 μRadians in one spill. Beam tests[18, 19] of these chambers indicate an order of magnitude safety factor in particle flux over the 10^9/cm^2/spill expected in NuMI before space charge buildup affects their operation.

3. Conclusions

The NuMI beam will turn on in 2004, with the first experiment, MINOS, ready to take data. Beyond MINOS, a potential physics program is to exploit the intense NuMI beam in an off-axis experiment, where sensitivities to $\nu_\mu \to \nu_e$ at the percent level would allow competitive measurements to see if this rare transition is large enough for CP violation studies. Additionally, the NuMI physics program is unique and complements that at the JHF in that matter effects and the neutrino mass hierarchy may be explicitely studied along with the potential CP-violating phase δ.

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